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A Direct Recording Method of Measuring Magnetic Flux Distribution

by

F. S. Dellenbaugh, Jr.

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A Direct Recording Method of Measuring Magnetic Flux Distribution

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GENERAL PROBLEM

In undertaking an investigation in some of the more elusive refinements of dynamo-electric machinery design it became necessary to measure and analyze such a multitude of curves of flux distribution, that the labor and time required by existing methods practically prohibited the investigation. After some experimentation the method described was developed, which has the advantages of speed, accuracy and minimum effort in producing results.

This apparatus represents merely one detail of the means toward an end, and is rough in construction, being assembled from materials at hand, but the results are so satisfactory that it was thought advisable to describe the method in order that others might avail themselves of its simplicity.

PRINCIPLE OF APPARATUS

The most common method of measuring flux distribution involves a search coil and ballistic galvanometer. Those who have worked with this method will readily appreciate the time involved in making a detailed survey of a magnetic field of any extent. Other methods such as the Grassot fluxmeter, change in resistance of bismuth wire, integrating volt-second meter etc. were investigated, but for one reason or another did not lend themselves aptly to the particular problem.

A revolving search coil fitted with a collecting device and operating at a high and constant speed was then thought of. The only objection seemed to be possibility of contact trouble at the brushes. The principles involved are the same as in any rotating generating machinery, the particular form of the parts being extreme. There appears to be no record of its having been previously tried, in spite of its simplicity of idea and somewhat obvious application.

In brief the apparatus consists of a search coil of very small diameter, and length approximately equal to the surface across which the flux distribution is to be examined, wound with a closed-coil winding and fitted with a commutator. The coil is rotated by a small storage battery motor, fitted with a governor to control the speed, and a magneto to indicate the speed. The voltage generated in the coil will then be proportional to the flux density of the field in which it rotates, other factors being constructed or maintained constant.

This voltage may then be read on an indicating meter or better, projected upon a photographic recording device by a reflecting instrument. The commutator was chosen rather than slip rings, first, because the component density in a definite plane may thus be determined, and second, because of the greater sensitivity and simpler technique obtained with direct-current instruments.

DETAILS OF CONSTRUCTION

Fig. 1 shows a drawing of the search coil. The "armature core" is constructed of bakelite to avoid eddy currents, 0.22 inches in diameter, about four in. long, and has four slots 0.05 inch wide by 0.07 inch deep. On each end a brass cup is attached, the small one on the left being merely a bearing to steady the coil, and the long extension on the right carrying the commutator and extension for attachment to the driving motor.

A four-part commutator is used, as a compromise between too greatly fluctuating voltage with two parts, and two great construction difficulties with a greater number of parts. The bars are made of gold, mounted upon a hard rubber sleeve and held in place by hard rubber "shrink rings" reinforced with brass. The dimensions of the commutator are 0.25 in. diameter by 0.15 in. face.

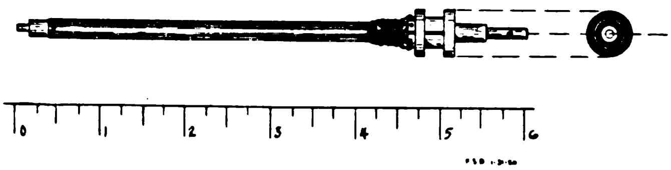

Fig. 1—Search Coil. Bakelite Core, Four Slots, Four Bar Commutator.

The winding consists of five turns per coil of No. 38 d. s. c. copper wire, connected in the usual closed coil manner, with the bars placed so that a line drawn through the commutating points is in the same plane as the magnetic field generating the voltage, and the brushes therefore at right angles to the field, tangential type being used. This allows the coil to be approached close to the magnetic surface being explored. The brushes themselves consist of laminated strips of thin phosphor bronze tipped with silver, and are mounted so that they may be rotated around the commutator through 180 deg.

The coil is driven by a small motor, in this case a six-volt "Klaxon" horn motor being used. It is considerably larger than necessary but it was the smallest available. Fig. 2 shows the complete assembly of coil

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motor, and governor. The magneto was not attached at the time the photograph was made. The second rod projecting from the bottom of the motor is a steady-rest for the end of the coil, as otherwise it will not run entirely true due to slight unbalance and slight warp in the bakelite.

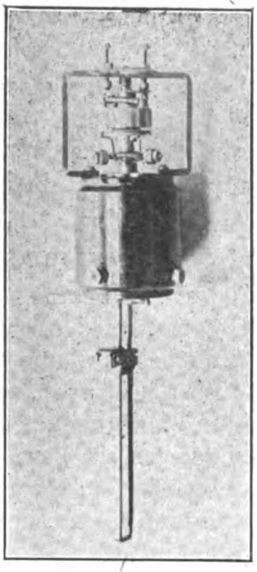

FIG. 2—SEARCH COIL AND DRIVING MOTOR SHOWING COIL AND STEADY REST, WITH GOVERNOR ON TOP OF MOTOR

SPEED CONTROL

As the speed control is very important, Fig. 3 shows a drawing of the governor, which is a combined centrifugal and inertia type. The collar *D* carries a shaft which runs up through the whole device. It also has fixed to it a plate which carries the three centrifugal weights *W* at the ends of the bell-crank arms *C*. These weights are threaded upon their carrying pins in order to balance for running speed. When these weights fly out they push up on the plate *B* which lifts both the flywheel *F* and the friction plate *P*, and forces the latter against the leather friction rubbers *L*. So far it is similar in action to the well-known phonograph governor. It was found, however, that this type alone allowed small instantaneous fluctations or jumps in speed, which would occur before the centrifugal weights had time to act, and introduced breaks and inequalities in the recorded results. Therefore the flywheel *F* was added. This runs loose upon the sleeve *K*, which sleeve carries the friction plate, and is keyed to the shaft so that it can rise and fall, but must turn with the motor. Therefore the flywheel running loose upon this sleeve will tend to run ahead or behind as the motor is retarded or accelerated. The upper end of the flywheel has two sloping notches in which rest pins attached to the friction plate sleeve. Thus rotation of the flywheel with respect to the sleeve tends to raise the friction plate when in one direction, and allows it to fall when in the other direction. Thus very small fluctuations in speed are immediately corrected by the

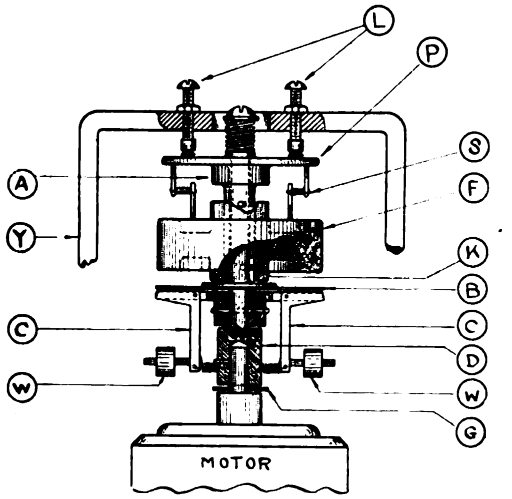

FIG. 3—GOVERNOR. COMBINED INERTIA-CENTRIFUGAL TYPE FOR CONTROLLING SPEED

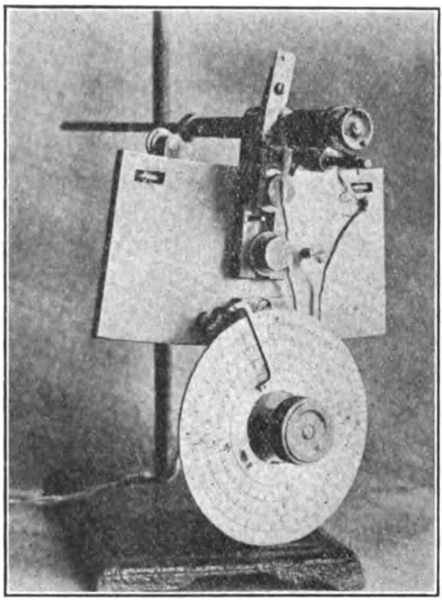

FIG. 4—CARRIAGE FOR SEARCH COIL. IN THIS CASE WITH TYPE OF COIL USED WITH BALLISTIC GALVANOMETER. MOTOR DRIVEN COIL REPLACES PART MOUNTED ON SLOTTED BRACKET

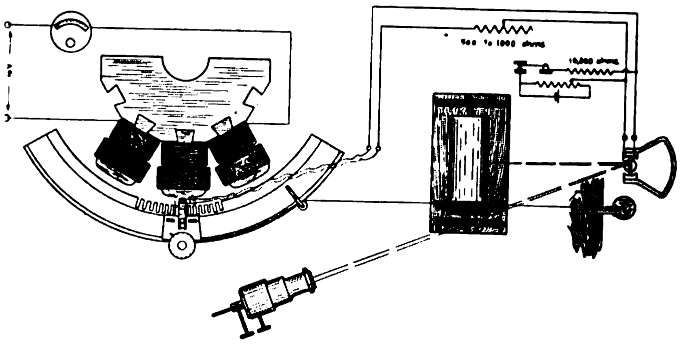

FIG. 5—GENERAL ARRANGEMENT OF TEST APPARATUS. SHOWING TEST COIL CARRIAGE, SECTION OF ALTERNATOR PUNCHINGS BEING EXAMINED, REVOLVING DRUM, REFLECTING METER, AND ARC LIGHT

flwheel shifting its position with respect to the sleeve and increasing or decreasing the pressure upon the friction rubbers independently of the centrifugal weights. Very light springs *S* locate the normal position of the flywheel so that the pressure upon the friction plate is always carried through the pins and sloping notches.

Speed Measurement

A small magneto, not shown, is attached to the top of the whole assembly and is calibrated to read speed with an indicating millivoltmeter. This consists of a shuttle type armature 0.35-in. diameter wound with 200 turns No. 40 d. s. c. wire connected to a two-part commutator, and excited by a permanent magnet from a small voltmeter, the magnet being circular and about 2.5 in. in diameter. The voltage generated is about 100 millivolts at 2000 rev. per min. and as the peripheral speed of the commutator is only 80 feet per minute, no trouble with commutation has been found.

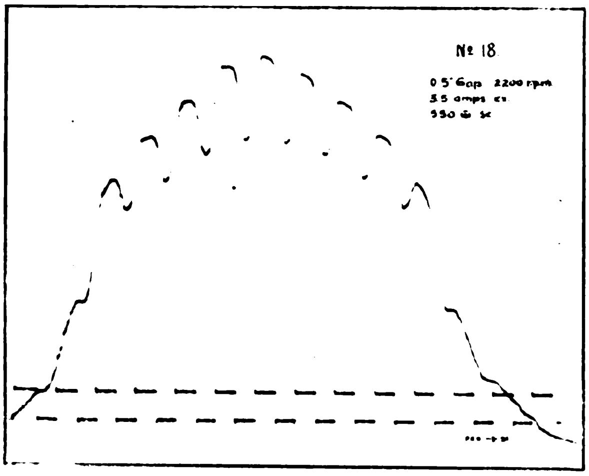

Fig. 6—Flux Distribution in Air Gap. 0.5-in. Air-Gap, Coil Moved Along Core Face. Position of Teeth Shown at Bottom

Recording Device

Some difficulty was experienced in obtaining a reflecting instrument that would follow quickly and truly the variation in voltage generated in the search coil. Galvanometers were too sluggish when critically damped, and would overshoot when not damped. The ordinary standard millivoltmeter has too low resistance and required enough current to cause commutating troubles, as well as large errors due to drop in coil. Vibration galvanometers or oscillograph elements either required too much current, or would pick up the frequency of commutation and vibrate continuously. Therefore a Weston ammeter was rewound with No. 40 d. s. c. wire, enough being wound on the moving coil to give 144.6 ohms resistance. The needle was bent back over the suspension, and a mirror fastened upon it centrally over bearings. This was found to give excellent results. It is very nearly critically damped and follows any change in voltage with great rapidity. Its sensitivity is quite high, giving a deflection of one cm. at one meter with 2.14 millivolts across its terminals, or 0.0148 milliamperes through the coil. This is about ten times the sensitivity of the standard millivoltmeter.

Arrangements of Apparatus

For the immediate problem in hand a section of a 12-pole alternator is set up horizontally on a table, the field coils excited, and the core being bare. A carriage running on a wooden track concentric with the core face carries the search coil assembly. Fig. 5 shows the arrangement schematically. A curved rack on the wooden track meshes with a gear on the carriage, and the gear carries a micrometer head graduated so that the position of the coil can be read to 0.05 tooth pitch. The search coil is mounted upon a slotted bracket so that it can be moved through any given plane in the air gap. Fig. 4 shows the carriage with an old type of search coil in place, which was rotated by a spring through 180 deg. when released by a trigger to obtain readings with a ballistic galvanometer. This is replaced directly by the present device, the remainder of the carriage remaining the same.

The reflecting meter is mounted upon the extreme right, and light from a small arc lamp, shown in lower center, is reflected upon a large drum. A small wire connects the drum pulley to the search coil carriage, and thus rotation of the drum is a function of the search coil position. The wire is arranged by means of pulleys so that it follows the arc of the wooden track, and after going once around the drum pulley, is attached to a counterweight.

The reflecting meter is connected to the search coil and also to a second circuit in parallel operated by a key. This is used to locate definite points on the curve by giving a small deflection when the contact is closed.

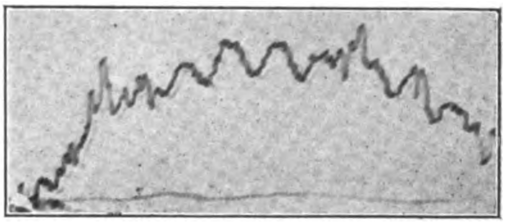

Fig. 7—Curve Obtained Without Governor and Commutator Improvements. Same Conditions as Fig. 6

Results Obtained

Fig. 6 shows the curve of flux distribution in the air gap along the armature core face. The positions of the teeth are shown at the bottom, being put in by means of the hand-operated key after the other curve had been made. The lines representing the bottoms of the slots are also the zero line of the curve. The depth of the slots is not to scale, but the width of the teeth and slots is accurate to 0.05 tooth pitch. The small wiggles in the curve at some places appear to be due to irregularities in the surface of the wooden track, as they are duplicated in the same spot with all curves.

Fig. 7 shows one of the first curves made before the motor was governed, and when there was also some vibration in the brushes. It is included here for contrast and to indicate how successfully it is possible to eliminate the various sources of error.

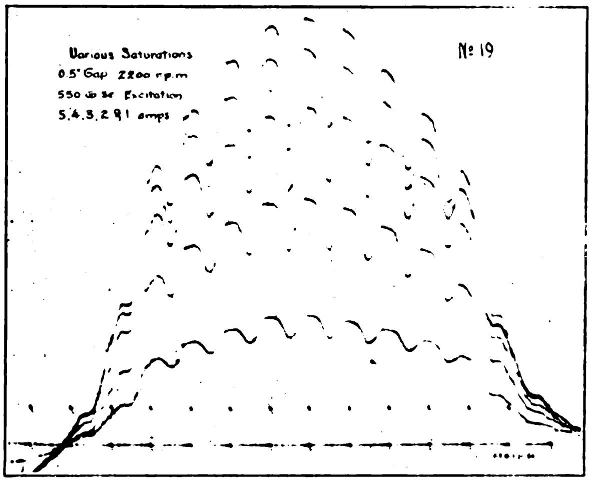

FIG. 8—FLUX DISTRIBUTION FOR VARIOUS SATURATIONS. POINTS ABOVE ZERO LINE INDICATE CENTERS OF TEETH

Fig. 8 shows a series of curves made at various saturations with the search coil close to armature core face. The saturation did not reach a high enough value to obtain noticeable change in the "tooth tufting". The maximum value of density was in the neighborhood of 8000 gausses in the air gap. The zero line was put in by a second rotation of the drum with the search coil disconnected, and the dots above it represent the centers of the teeth, put in by means of the second circuit and key.

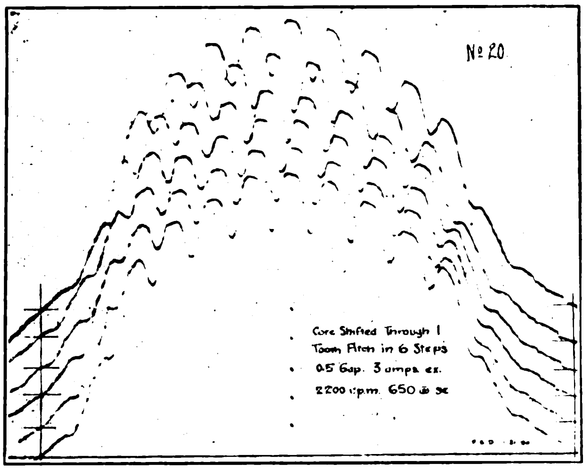

FIG. 9—FLUX DISTRIBUTION FOR VARIOUS RELATIONS OF TEETH TO POLE. CORE MOVED A LITTLE AROUND POLE FOR EACH CURVE. TOTAL MOVEMENT FROM FIRST TO LAST CURVE ONE TOOTH PITCH. ZERO LINE OF EACH CURVE DISPLACED FROM PRECEDING ONE TO AVOID CONFUSION

Fig. 9 shows the distribution of flux for the same saturation, but with the core shifted slightly with respect to the pole for each curve. The total shift between the top and bottom curves was just one tooth pitch, but the intermediate positions were not even fractions of the tooth pitch, although it was attempted to get them close to 1/6 pitch each, in order to obtain a smooth series. The zero point of each curve was displaced in order to avoid over-lapping and too much confusion.

The air gap in all the above curves was normal, 0.5 inch. In Fig. 10 the gap was increased to 1⅛ inches in order to exaggerate the results. Curves were then made for various positions of search coil from close to core face to close to pole face. The zero lines were displaced as before to avoid overlapping. The unbalance noticeable in the curve along pole face is due to the fact that only three poles are present, the distribution being investigated under the middle one, and slight differences in reluctance of either side pole unbalances the flux.

These curves are all made directly on photographic paper, size eight by ten inches, and have a base of about nine inches by maximum ordinate of about seven inches. This is convenient size, both for further treatment, and because they will file easily in standard letter file. The convenience of using paper instead of films eliminates a good deal of bother owing to a dark-room being unnecessary. All curves shown were made in an ordinary room in day time with the shades pulled down and black muslin hung up where the light was too intense. An old carbon incandescent lamp was used for local illumination to determine the setting etc. and is perfectly safe with most "gaslight" papers. The search coil is moved through the gap at a speed of about two feet per minute, and so gives ample time for exposure. It can be operated at about twice this speed without distorting the curves, and can be operated slower if longer exposure is necessary. Any "gaslight" paper may be used, these particular curves being made on AZO Hard-X developed in letol-Hydroquinone developer deficient in sodium carbonate, and well loaded with potassium bromide and potassium iodide

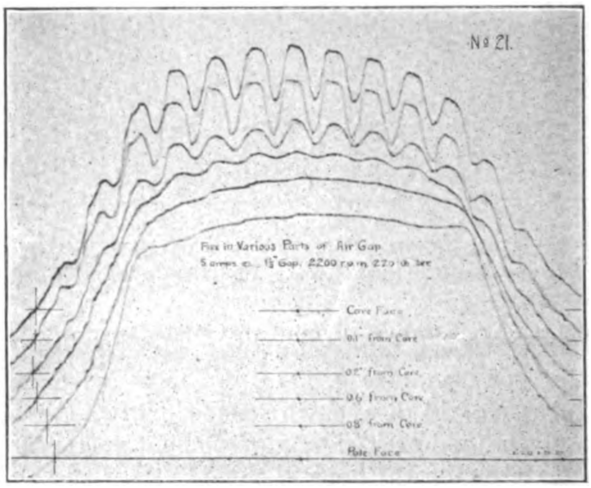

FIG. 10—FLUX DISTRIBUTION AT VARIOUS POINTS IN AIR GAP BETWEEN CORE FACE AND POLE FACE. AIR GAP INCREASED TO 1 1/8 IN. ZERO LINE OF EACH CURVE DISPLACED FROM PRECEDING ONE TO AVOID CONFUSION

to give as much contrast as possible and cut down the small amount of fog present.

ACCURACY

Enough work has not as yet been done with this apparatus to determine definitely the accuracy to be expected, but it seems to be quite high. The speed control holds to within 0.1 per cent for short periods, and within 1 to 2 per cent for periods of an hour or so. The speed can be read by the magneto to within 0.5 per cent easily, and the larger variation corrected before making a curve.

The contact resistance at the brushes of the search coil varies somewhat, but is very small percentage of the total resistance in circuit. The resistance of the search coil and brushes measured under conditions of speed varying from standstill to 3600 rev. per min. and current varying from normal to several hundred times normal, gave extremes of 1.23 ohms and 1.57 ohms. In actual use from 500 to 1000 ohms is used in series with the coil and reflecting meter, and 144.6 ohms in the meter circuit, makes a total minimum of about 646 ohms. The total variation in resistance of the coil is only 0.34 or 0.0525 per cent and so entirely negligible.

Under normal conditions the distance of drum to mirror is 24 in. and maximum ordinate 7 in., which requires a current in the meter coil of 0.434 milliampere. This gives an error of only 0.46 per cent if we neglect the resistance of coil and leads entirely. Its distortional effect upon the field being measured appears to be entirely negligible.

The accuracy of converting coil voltage to flux density depends upon the accuracy with which we can determine the area of the cross-section of the windings on the coil. By the ordinary theory of generating machines we find that the flux density is determined by the formula:

$$B = \frac{E \times 60 \times 10^8}{2.548 \times \pi \times \text{rev. per min.} \times n \times A} \text{ for four-coil winding}$$

where: B = Flux density in which coil operates.
E = Voltage coil generates.
n = Turns per coil in winding of search coil = 5.
A = Area of one coil of winding on search coil.

Thus the value of A is the only one indeterminate. In the present case this is about 0.06 square inch. It has also been found that the best operating speed is from 1800 to 2500 rev. per min. Below these limits uncontrolled friction is too great a part of motor load and the speed varies, and for higher values it does not run sufficiently well in balance to avoid vibration and difficulty with commutation. All the curves shown were made at a speed of 2200 rev. per min. It will be seen that the generated voltage has a magnitude of from 200 to 500 millivolts for normal air gap densities. Probably the most accurate way of determining the relation between voltage and flux density would be by calibration against a definite smooth magnetic field set up by a special magnet, and measured by ballistic galvanometer methods. This is a little roundabout, but by many trials and different conditions should lead to an accuracy of 1 per cent.

Therefore in general we should expect a combined accuracy of well within 2 per cent, and possibly within 1 per cent. It is believed that this compares favorably with other methods of obtaining similar results.

SPEED OF OBTAINING RESULTS

The time necessary to obtain one curve such as Fig. 6 by means of a ballistic galvanometer and point by point plotting method was at least an hour and a half and usually two hours. The time to make Fig. 6 was five minutes including all adjustments and developments.

Fig. 8 took ten minutes, for although having five curves, the majority of the time is required for setting up the various parts and making preliminary adjustments.

Fig. 9 took twenty minutes, since the adjustments between curves were more laborious.

A total of 31 curves was made easily in three hours, which works out at about six minutes per curve for an average, including adjustments of all kinds, and the usual details connected with any tests of this sort.

In an investigation such as the one under consideration where at least a thousand of such curves must be made, the time for making them by ballistic galvanometer method would be something of the order of two years, on the part time basis covering this investigation and is reduced to approximately five weeks by the above described device.

FURTHER DEVELOPMENTS

It is probable that a silver commutator and silver brushes similar to those used on d-c. integrating wattmeters would give more satisfactory results than the combination of gold and silver. The latter needs occasional lubrication with a trace of graphite. The motor could be reduced considerably in size and probably some form of synchronism motor would eliminate speed troubles. It is hoped shortly to reconstruct the device, so that the search coil will be still smaller in diameter, fully enclosed, so that it may be moved by hand against surfaces investigated and not require a track and carriage, and the driving mechanism all enclosed in a handle. In this form the whole thing will be light and portable. A small governed motor-generator set will probably provide a desirable form of power, machines the size of 8-in. fan motors probably being large enough, and operated from a six-volt storage battery. The recording device can be made much less bulky and arranged to fold like a camera, so that it becomes easily protable. A tungsten lamp would probably give enough light for drawing the curves, and the apparatus can be loaded in a dark corner or under a blanket and does not require a dark-room and safe lights. When these improvements have been made it will be possible to carry it to a machine anywhere and investigate flux distribution in detail with convenience and dispatch.

LIST OF RESEARCH BULLETINS

Bulletin Number

*1. The Economical Transportation of Merchandise in Metropolitan Districts. H. Pender and H. F. Thomson; March, 1912.

2. Notes on the Cost of Motor Trucking. H. Pender and H. F. Thomson; October, 1912.

*3. Observations on Horse and Motor Trucking. H. Pender and H. F. Thomson; March, 1913.

4. Relative Fields of Horse, Electric and Gasoline Trucks. H. F. Thomson; August, 1914.

*5. The Delivery and Handling of Miscellaneous Freight at the Boston Freight Terminals. H. Pender, H. F. Thomson, and C. P. Eldred; February, 1914.

6. The Delivery System of R. H. Macy & Co. of New York. H. F. Thomson, H. L. Manley and A. L. Pashek; September, 1914.

7. Explorations over the Vibrating Surfaces of Telephonic Diaphragms under Simple Impressed Tones. A. E. Kennelly and H. O. Taylor; April, 1915.

8. The Mechanics of Telephone-Receiver Diaphragms as Derived from their Motional-Impedance Circles. A. E. Kennelly and H. A. Affel; November, 1915.

9. Experimental Researches on Skin Effect in Conductors. A. E. Kennelly, F. A. Laws and P. H. Pierce; September, 1915.

10. Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds. A. E. Kennelly and O. R. Schurig; June, 1916.

11. Some Properties of Vibrating Telephone Diaphragms. A. E. Kennelly and H. O. Taylor; April, 1916.

12. Experimental Researches on the Skin Effect in Steel Rails. A. E. Kennelly, F. H. Achard and A. S. Dana; August, 1916.

13. Skin-Effect Resistance Measurements of Conductors at Radio-Frequencies up to 100,000 Cycles per Second. A. E. Kennelly and H. A. Affel; December, 1916.

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20. Alternating-Current Planevector Potentiometer Measurements at Telephonic Frequencies. A. E. Kennelly and Edy Velander; July, 1919.

21. A Theory of Metallic Ore Welding. Ralph G. Hudson; March, 1920.

22. Oscillographs and Their Tests. A. E. Kennelly, R. N. Hunter and A. A. Prior; April, 1920.

23. A Direct Recording Method of Measuring Magnetic Flux Distribution. F. S. Dellenbaugh, Jr.; October, 1920.

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